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KINEMATIC HISTORY OF THE TRIASSIC SOUTH OF THE INN VALLEY (NORTHERN CALCAREOUS ALPS, AUSTRIA) - EVIDENCE FOR JURASSIC AND LATE CRETACEOUS LARGE SCALE NORMAL FAULTING

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Kinematic history of the Triassic South of the Inn Valley (Northern Calcareous Alps, Austria) - Evidence for Jurassic and Late Cretaceous large scale normal faulting

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ABSTRACT - The geometry of slices at the southern margin of the Northern Calcareous Alps not only calls for thickening of the nappe stack by compression, but also thinning of the sedimentary column by extension. The deformational history of the Triassic south of the Inn Valley is characterised by six stages: (1) Thinning by top SE extension during Jurassic continental breakup, (2) stacking of thinned slices by top NW thrusting during the time of peak temperature metamorphism at 140 Ma (Early Cretaceous), (3) postmetamorphic top SE extension (Late Cretaceous) contemporaneously with Gosau sedimentation on top of the nappe pile of the Northern Calcareous Alps and (4) a long period of N-S compression (Eocene), resulting in northvergent thrusting and folding with development of a foliation, southvergent thrusting and, finally, overturning of the strata in the western part of the investigated area. (5) In the Oligocene and Miocene minor sinistral strike slip faulting is recorded. (6) Normal faulting along WSW-ENE trending planes.

Key words : Polyphase deformation, Jurassic extension, Late Cretaceous extension, Northern Calcareous Alps, Greywacke Zone, coalification, conodont alteration index.

ABSTRACT - La geometria delle scaglie localizzate sul margine sud delle Alpi Calcaree Settentrionali non indica solo un ispessimento della pila di falde per compressione, ma anche un assottigliamento della colonna sedimentaria per estensione. La storia della deformazione del Triassico a sud della Valle dell'Inn è caratterizzata da sei stadi: (1) = assottigliamento con estensione *top* verso SE durante la rottura continentale giurassica; (2) = appilamento di scaglie assottigliate per compressione con *top* verso NW al tempo del picco termico del metamorfismo, a 140 Ma (eo-Cretaceo); (3) = estensione postmetamorfica con *top* a SE (tardo Cretaceo) contemporanea alla sedimentazione di Gosau al tetto della pila di falde delle Alpi Calcaree Settentrionali, e (4) = un lungo periodo di compressione N-S (Eocene), che risulta in un thrusting nord-vergente e piegamento con sviluppo di una foliazione, thrusting sud-vergente, ed infine rovesciamento degli strati nella parte occidentale dell'area studiata; (5) = movimenti minori per faglie trascorrenti nell'Oligocene e Miocene; (6) = faglie normali lungo direzioni WSW-ENE.

Parole chiave : Deformazione polifasica, estensione giurassica, estensione tardo-Cretacea, Alpi Calcaree Settentrionali, Zona delle Grovacche, indice di alterazione dei conodonti, coalificazione.

INTRODUCTION

The Northern Calcareous Alps represent a thin-skinned fold-and-thrust belt along the northern margin of the Austroalpine nappe pile. The major nappe units in the western Northern Calcareous Alps are, from bottom to top: lower Bajuvaric (Allgäu) nappe, upper Bajuvaric (Lechtal) nappe and Tirolic (Inntal) nappe (Tollmann, 1976). The Greywacke Zone forms the basement of the Tirolic nappe. The study area is located in the westernmost part of the Tirolic unit (Fig. 1).

The stratigraphic succession of the western Northern Calcareous Alps in the investigated area reaches from the Permian to the Late Oligocene. The sediments were deposited on the northwestern passive continental margin of the Tethys ocean (Tollmann, 1976). In the Late Cretaceous, the Northern Calcareous Alps were involved in an orogeny in lower plate position related to the closure of the Meliata ocean in the southeast (*e.g.* Neubauer, 1994). The southern margin of the Northern Calcareous Alps was overprinted by low to very low grade metamorphism during this event (Kralik *et al.,* 1987). Late Cretaceous sediments deposited on top of the nappe stack (Gosau Group) are considered as synorogenic. Gosauian sediments in the central part of the Austroalpine were deposited above large scale top E low angle normal faults (Neubauer *et al.,* 1995), whereas the tectonic setting of these synorogenic basins is still not well understood for the Northern Calcareous Alps.

From the Early Jurassic onwards the Penninic ocean opened to the northwest of the Northern Calcareous Alps. The closure of this ocean led to orogeny in Tertiary times (Eocene to Miocene), when the Austroalpine nappes were transported onto the European foreland.

The timing of the tectonic and metamorphic events at the southern margin of the western Northern Calcareous Alps is investigated in this study by detailed mapping (1:10 000 and 1:5000 scale) combined with stratigraphy,

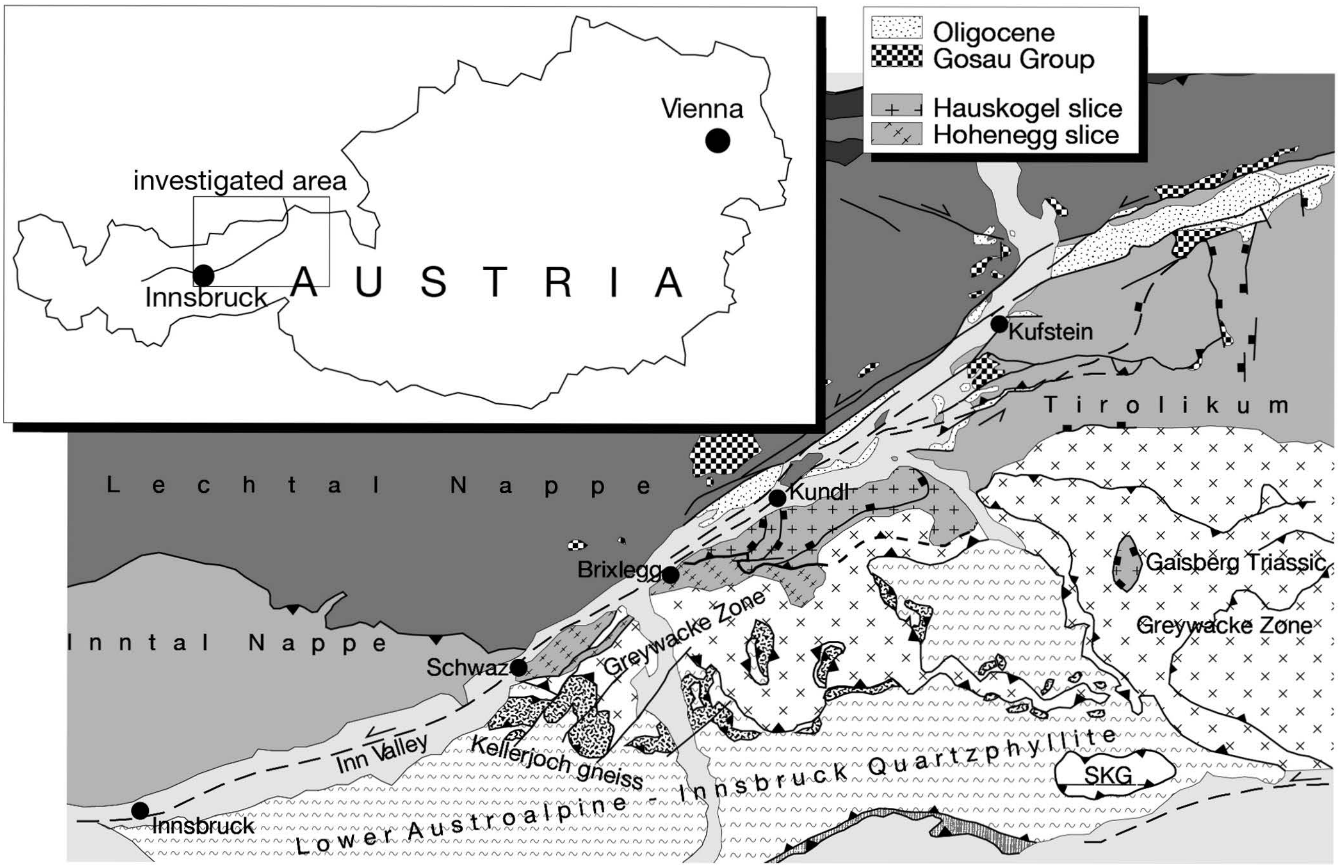


Fig. 1 - Location of the investigated area and tectonic sketch map. SKG = Steinkogel Gneiss.

structural analysis and paleotemperature-estimations (vitrinite reflectance and conodont alteration index).

STRATIGRAPHY

Because proper recognition of lithostratigraphic units is crucial for the clarification of the complicated tectonic pattern in the area of investigation, a short characterisation of the units follows (*cf.* Fig. 2):

The Greywacke Zone mainly consists of Lower Paleozoic meta-pelites (Wildschönau Phyllites) and the Schwaz Dolomite, a thick carbonate succession of Devonian age. Locally the base of the Schwaz Dolomite is formed by a quartzite of 10 cm to several meters thickness, that allows to identify the sedimentary contact of the Schwaz Dolomite to the Wildschönau Phyllites. Both units were deformed and reached greenschist facies conditions during Variscan orogeny.

Permoscythian sediments transgress onto the Wildschönau Phyllites and, more commonly, on Schwaz Dolomite; locally with a basal breccia, almost entirely made up of clasts from the underlying lithology. The Gröden Formation directly overlies the Wildschönau Phyllites and the Schwaz Dolomite in a few locations. It consists mainly of coarse cross-bedded conglomerates with quartz-pebbles and immature sandstones with siltstone intercalations.

Upsection, an interval of red-weathering, structureless medium bedded quartzites alternating with thin clay horizons and intercalations of siltstones and conglomerates (Lower "Alpiner Buntsandstein") follows. The Upper "Alpiner Buntsandstein" consists of light red to white trough cross bedded sandstones. The uppermost part of the Permoscythian at the transition to the overlying Reichenhall beds locally has thick gypsum horizons and green claystones interlayered with sandstones (Werfen beds). The Reichenhall beds consist of rauhwackes and gypsum as well; locally thin-bedded dolomites and yellow carbonate sandstones are present.

The Alpine Muschelkalk Group represents a carbonate ramp from a shallow water environment (Steinalm Formation), transitional facies (Annaberg, Virgloria Formations) to basinal conditions (Gutenstein Formation). The individual formations of this group display great variability both laterally and vertically. The lowermost unit of this group is the Gutenstein Formation that consists of dark grey to black well-bedded limestones. In the Gaisberg area in the lower part of the Gutenstein Formation, limestones and black marls alternate. In the Schwaz-Wörgl area, the Gutenstein Formation can laterally be replaced by the Annaberg Formation, a succession of Sdm-bedded limestones frequently with crinoids, often dolomitized, with nodular bedding planes. Another lateral equivalent of the Gutenstein limestones is the Virgloria Formation, that consists of thin-bedded bioturbated limestones and thin marly interbeds. In areas, where there has been no clastic influence, the Steinalm Formation developed, with light grey massive limestones containing dasycladacean algae, or, more commonly dolomites.

Except in the Gaisberg Triassic (Fig. 1), where the Wetterstein Dolomite gradually develops from the Gutenstein Formation, the Annaberg Formation or Steinalm Dolomite is followed by the Reifling Formation. The Reifling Formation consists of nodular well-bedded limestones with frequent silica nodules and intercalations of calcareous marls and tuffites.

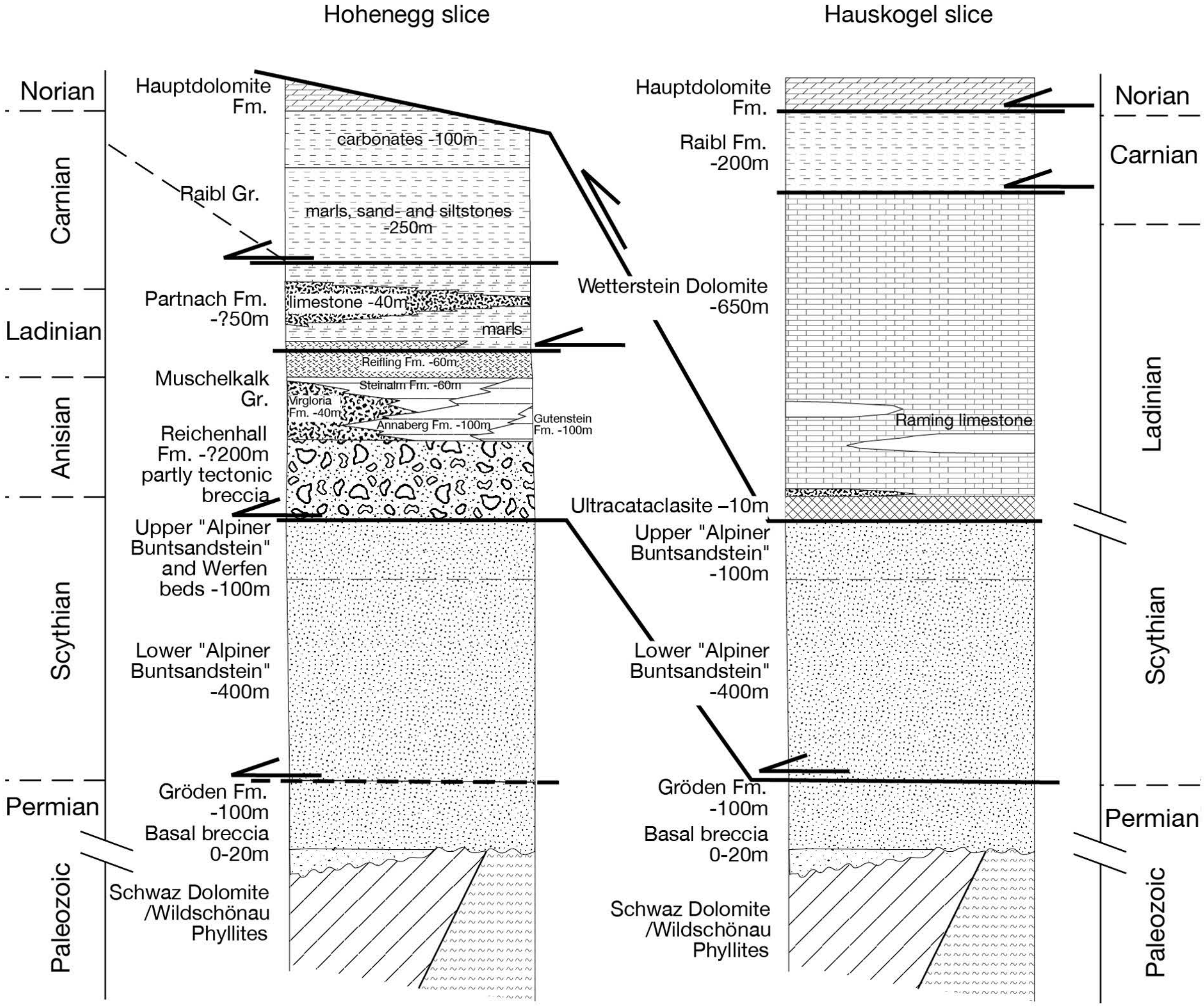


Fig. 2 - Tectonostratigraphy of the investigated region. The thicknesses of the intervals correspond to the thicknesses found in the field. The lower decollement cutting both columns represents the situation east of Kundl; the upper detachment refers to the situation in the area west of Kundl (comp. Fig. 1).

The rocks younger than the Alpine Muschelkalk Group are different in the two tectonic units in the area (Figs 1, 2). The Partnach Formation in the *Hohenegg slice* (footwall unit) indicates a deepening of the sedimentation area and consists of dark brown to black calcareous marls and shales with one or more thick black limestone beds in between. The Raibl Formation develops gradually from the Partnach Formation, the deposition of black marls continues, but the siliciclastic content of the marls rises, often small detrital micas can be seen on bedding planes, and siltstone beds are intercalated. In the middle part of the succession of black marls, quartz sandstones and a thick black limestone bed (~2 m) are intercalated. The upper part of the Raibl Formation consists of limestones with oncoids, well-bedded dolomites with quartz nodules and echinoderm debris, dolomites with stromatolithic lamination, sedimentary intraformational breccias and lumachelles. At its top, the contact to the overlying Hauptdolomite Formation is locally formed by rauhwackes of the Raibl Formation. The Raibl Formation is overlain by the well-bedded bituminous dolomites of the Hauptdolomite Formation.

In the *Hauskogel slice* (hangingwall unit), the Raming Limestone a transitional facies between the Partnach Formation and the Wetterstein Dolomite is present. The Raming Limestone consist of biogenic detritus shed from the Wetterstein platform into the Partnach basin. The more distal parts of the Raming Limestone consist of thin-bedded black marly limestone. The proximal parts form grey limestone intercalations in the lower part of the Wetterstein platform carbonates. The basal part of the Wetterstein platform is built by massive Wetterstein reefal carbonates, the upper part consists of poorly bedded lagoonal deposits. The entire Wetterstein platform is dolomitized, however some structures like isopachous fringes of (former) fibrous calcite are still visible. Possibly, the Partnach Formation underlaid the Wetterstein platform, but was removed tectonically.

The Raibl Formation of the Hauskogel slice can be subdivided into three generally marly successions with thin limestone- and sandstone layers and three dolomitic successions inbetween. In isolated outcrops, the dolomites of the Raibl Formation cannot be distinguished from the Hauptdolomite Formation.

The overlying Hauptdolomite Formation consists of thin- to medium-bedded bituminous dark grey dolomites. It is the youngest unit preserved in the study area.

DEFORMATION

Deformation in the investigated area is complicated and polyphase. The Paleozoic rocks of the Greywacke

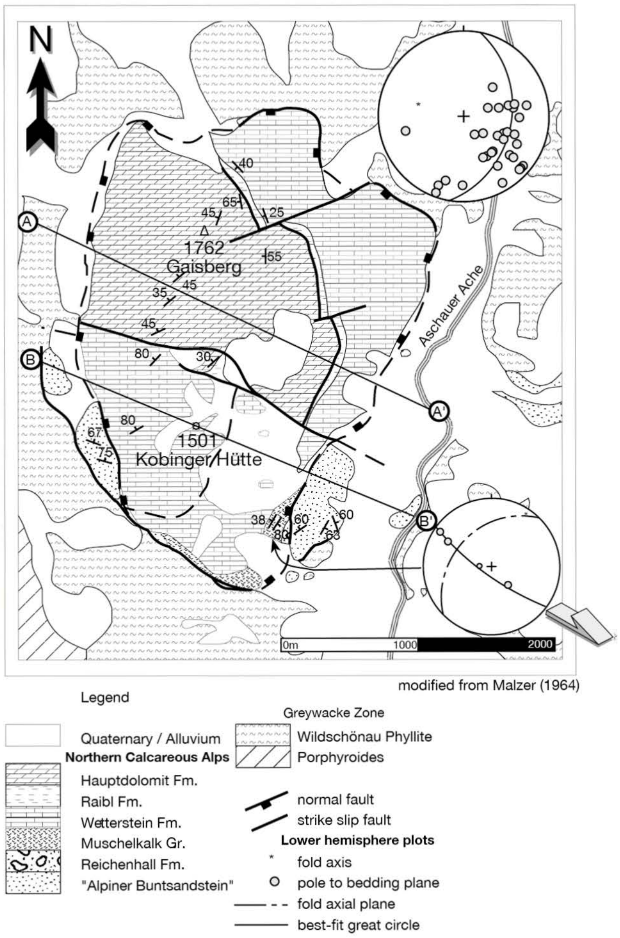


Fig. 3 - Geological sketch of the Gaisberg area. The diagram in the upper right corner illustrates the orientation of bedding planes in the Gaisberg Triassic. The lower right diagram shows the geometry of a m-scale fold above the decollement level, that indicates top ESE sense of movement.

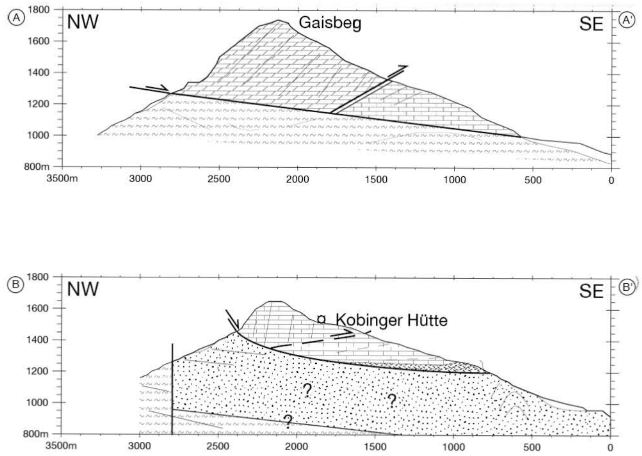


Fig. 4 - Cross sections of the Gaisberg Triassic. For location of cross sections and legend see Fig. 3. For explanation see text.

Zone experienced both Variscan and Alpine deformation. The pattern of deformation becomes increasingly complicated from east to west. In the following paragraphs, three subareas with contrasting deformational styles will be discussed separately.

Gaisberg area

The Gaisberg Triassic is a klippe of Permotriassic rocks ("Alpiner Buntsandstein" to the Hauptdolomite Formation) that rests tectonically on the Greywacke Zone. The main decollement level is the Reichenhall Formation. This is indicated by the geometric relationship between tilted Gutenstein limestones above the detachment and the "Alpiner Buntsandstein" from below the detachment. The Reichenhall horizon is an ultracataclasite, and the lowest part of the Gutenstein limestones is deformed into a cataclasite (Malzer, 1964). The axial planes of meter-scale folds above the decollement level dip to the WNW (Fig. 3), suggesting a top ESE movement at the decollement level.

In contrast to this semiductile/brittle deformation, conglomerate beds in the "Alpiner Buntsandstein" Formation above the main detachment are strongly deformed by ductile deformation. Limestone pebbles in this horizon are flattened, or form the matrix of less deformed dolomite pebbles and nearly undeformed quartz pebbles. The long axes of the deformed pebbles trend approximately north-south (Stingl, 1996), indicating a N-S movement during peak temperature conditions.

The Gaisberg Triassic is cut by a WNW-trending transfer fault, that separates two slightly different blocks. In the northern block, Wetterstein Dolomite, Raibl and Hauptdolomite Formations are tilted to the west and rest on Wildschönau Phyllites, only small remnants of "Alpiner Buntsandstein" are left north of the Gaisberg. South of the fault, below the Kobinger Hütte (Figs 3, 4) Gutenstein limestones and Wetterstein Dolomite dip gently to the west. Above the Kobinger Hütte, the Wetterstein Dolomite is subvertical.

The geometry of a WNW-ESE cross section of the Gaisberg Triassic (Fig. 4) suggests the development of an extensional allochthon: westward tilting of fault blocks during top ESE extension of the hanging wall on the subhorizontal decollement level. The detachment were the gypsiferous Reichenhall and Upper "Alpiner Buntsandstein" Formations. In the northern part of the Gaisberg area, the complete "Alpiner Buntsandstein" and Muschelkalk successions were removed at the decollement, whereas in the southern part, only the Upper "Alpiner Buntsandstein" is absent.

Measures by Kralik *et al.* (1987) indicate a jump in illite crystallinity across the decollement level. White mica fine fractions from phyllites of the Greywacke Zone show lower epimetamorphism (lower greenschist facies; $2\vartheta° < 0.25$). Limestone samples from the Gutenstein Formation (Anisian-Ladinian) of the Gaisberg Triassic were overprinted by lower anchimetamorphism ($0.34 < 2\vartheta° < 0.42$). Therefore, top ESE movement accompanied by westward tilting of fault blocks took place after the heating event. Additionally, flattened "Alpiner Buntsandstein" conglomerates were tilted during the top ESE movement. The flattening deformation probably took place during peak metamorphic conditions.

Brittle fault planes in the Gaisberg area indicate E-W extension and offset the decollement level on outcrop scale.

Brixlegg-Wörgl area

The Brixlegg-Wörgl area can be subdivided into two structurally different regions: The eastern part between Maukenbach and Wörgl, where Triassic sediments form the southern limb of a simple open E-W trending syncline (Fig. 5), and the western part, where most of the Triassic

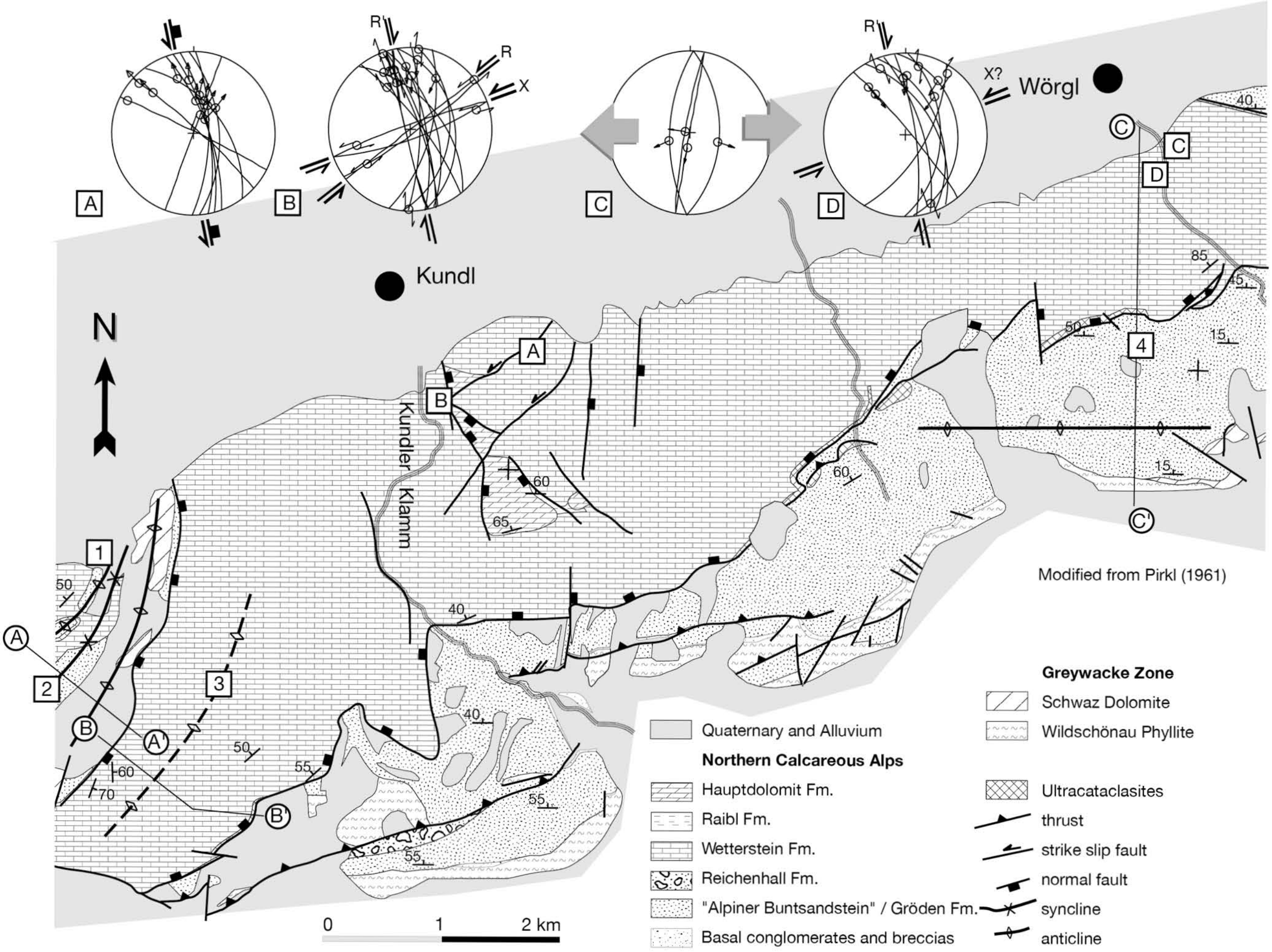


Fig. 5 - Geological sketch of the Kundl-Wörgl area. Most of the rocks belong to the Hauskogel slice, only the Wildschönau Phyllites, "Alpiner Buntsandstein" and Reichenhall beds in the lower left are part of the Hohenegg slice. Lower hemisphere plots: (A) young oblique extensional faulting; (B), (D) sinistral shearing; (C) normal faulting; R, R' ... synthetic and antithetic Riedel planes, X ... master fault. Figures 1-4 in squares denote locations of measurements in Fig. 6.

rocks are vertical to overturned, and the deformation is rather complicated (Fig. 10).

In the whole eastern part of the Brixlegg-Wörgl area, the Wetterstein Dolomite of the Hauskogel slice rests tectonically on the "Alpiner Buntsandstein", with an ultracataclasite horizon parallel to bedding of both units in between. The ultracataclasites are characterized by more than 90 % crushed rock material (Fig. 8; Heitzmann, 1985), and often show a well developed foliation (Figs 7, 8). The sense of movement can be interpreted from the geometry of asymmetric porphyroclasts and drag of foliation around them (Figs 7, 8). Meter-scale folds in the ultracataclasites of the Maukenbach indicate a top SSE-movement along the decollement (Fig. 9). The complete Muschelkalk Group was removed along the detachment zone. This is only possible between two ramps in the decollement. Therefore, a minimum estimate for the amount of top SE extension is the double width of the decollement level exposed in movement direction (6 km). The Hauskogel slice west of the Maukenbach displays thinning of the sedimentary succession as well. The Raibl Formation disappears along a fault horizon that follows the contact between Raibl and Hauptdolomite Formations. Brittle fault planes in Wetterstein Dolomite at the contact indicate top SE movements (Fig. 10D).

In the Hohenegg slice (footwall) south of Rattenberg, the Hauptdolomite Formation and the Raibl Formation trend obliquely to the thrust contact between the slices, whereas further east, the Raibl beds trend parallel to the contact. This structure can possibly be interpreted to represent a roll-over associated with top SE thinning of the Hohenegg slice. The basal thrust of the Hauskogel slice must have cut the Hohenegg slice, that already was deformed by the roll-over and removed part of the Hauptdolomite and Raibl Formations (Fig. 12A).

East of the Maukenbach, the Wetterstein Dolomite above the top SE decollement level is overturned and trends obliquely to the shear plane (Fig. 5). A NW-SE cross section (A-A', B-B', Fig. 6) across the anticline of the Maukenbach shows a roll-over anticline in the lagoonal Wetterstein Dolomite on top of the decollement level. The northwestern limb of the roll-over-anticline was steepened and overturned by subsequent NW-SE contraction. Synchronously, in the Maukenbach area, where the rigid Wetterstein Dolomite platform was thinned by normal faulting, an anticline developed, that brought the basement of the Hauskogel nappe to the surface. The anticline can possibly be interpreted as ramp anticline above the thrust between Hohenegg and Hauskogel slices. In the eastern part of the Brixlegg-Wörgl area the thrust between the Ho-

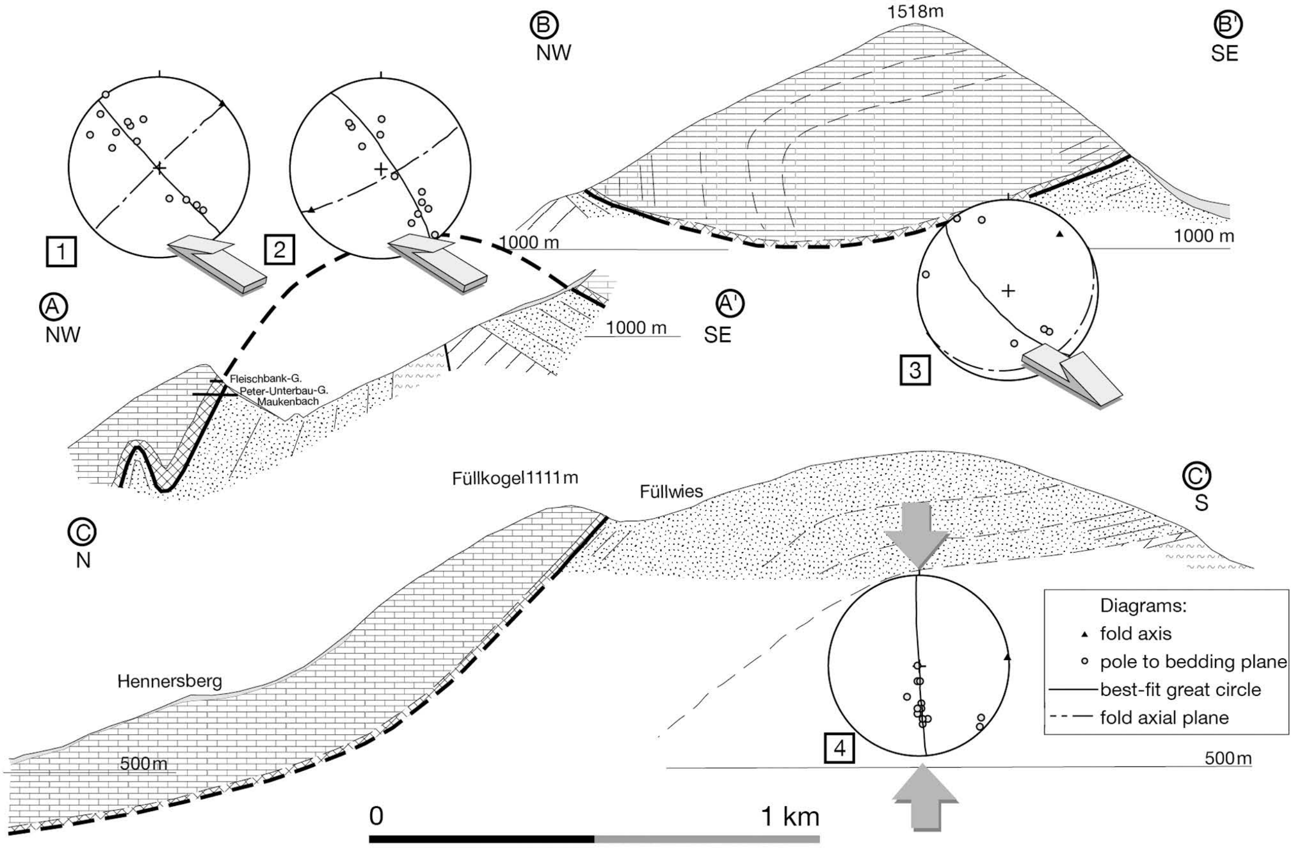


Fig. 6 - Cross sections from the Kundl-Wörgl area. For positions of cross sections and legend see Fig. 5. Figures 1-4 in squares denote locations of measurements in Fig. 5.

henegg and Hauskogel slice juxtaposes the Lower "Alpiner Buntsandstein" of the Hauskogel slice on top of the Reichenhall beds / Upper "Alpiner Buntsandstein" of the Hohenegg slice. In the area of the Maukenbach, a ramp in the thrust horizon exists, and west of the Maukenbach, the thrust stacks ultracataclasites of the Hauskogel slice onto Hauptdolomite / Raibl Formations of the Hohenegg slice (Figs 2, 12). The duplication of the Muschelkalk Group west of Reith (Fig. 10) could be a consequence of the top NW deformational event in the Hohenegg slice.

Between Wörgl and the Maukenbach and along the Wörgler Bach, the decollement is folded around younger E-W trending axes (Figs 5, 6/4). West of the Maukenbach, N-S-shortening is more intense, northward tilting affected the complete slice stack between the Maukenbach and St. Gertraudi (Fig. 10). The transfer fault parallel to the Maukenbach separates the tilted rocks from unaffected parts.

Fig. 7 - Ultracataclasite from the Maukenbach area. Note well developed foliation and asymmetric porphyroclasts. Shear sense is top to the left, which is SE.

N-S compression can be subdivided into several stages in the units affected by tilting. An early stage before tilting was associated with the formation of an axial plane cleavage in the Partnach shales and small scale fault-propagation folds. Before tilting, these folds indicated northvergent movements. The fold in the Reifling Formation west of the Tondlkopf (Fig. 10) is another larger scale example of such a structure (fold south of the Zimmermoosbach, cross section Fig. 11). A younger stage of N-S compression is characterised by southvergent thrusting. Most of the thrust planes cut the already folded stack and were overturned during tilting. Therefore, when measured in the field, they display a normal fault geometry. A thrust plane of this generation caused a doubling of the stratigraphy of the Hohenegg slice (Fig. 11).

The Triassic south of the Inn valley presumably is part of a large ramp anticline or fault propagation fold and forms its northern (overturned) limb.

Hauptdolomite and Raibl beds east of the Maukenbach are preserved in approximately N-S trending grabens, that developed during sinistral shearing along the Inntal fault (Fig. 5B) and younger oblique normal faulting along N-S trending sinistral faults (Fig. 5A). Sinistral faulting in this area was active after tilting. This might correspond to sinistral shearing along the Inntal fault (Ortner and Sachsenhofer, 1996). An older period of sinistral shearing can be dated to the Oligocene in the Tertiary rocks along the Inntal fault, and a younger event to the middle Miocene.

At the northern margin of the Hohenegg slice around Brixlegg (Fig. 10) a deeper unit of the slice consisting of Wildschönau Phyllites, "Alpiner Buntsandstein" and ultracatacla-

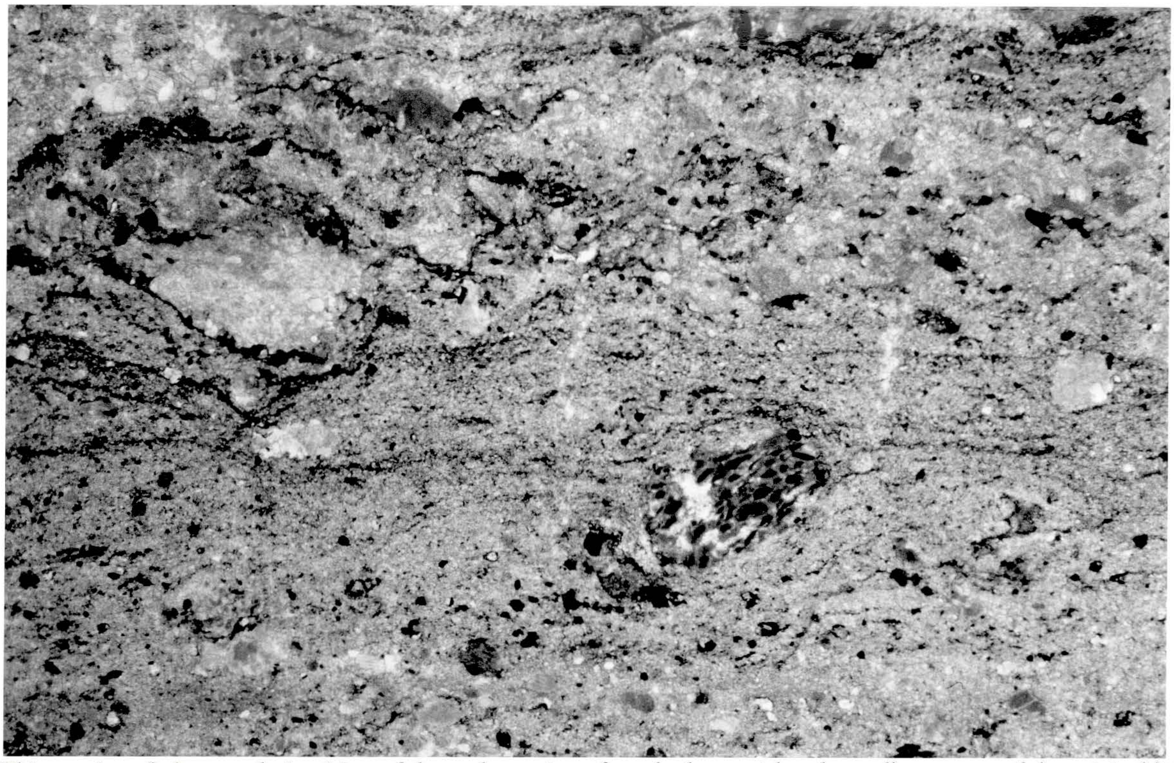


Fig. 8 - Thin section of ultracataclasite. Most of the rock consists of crushed material, only small remnants of the original lithology are present as porphyroclasts, that indicate the shear sense (top to the right, which is SE).

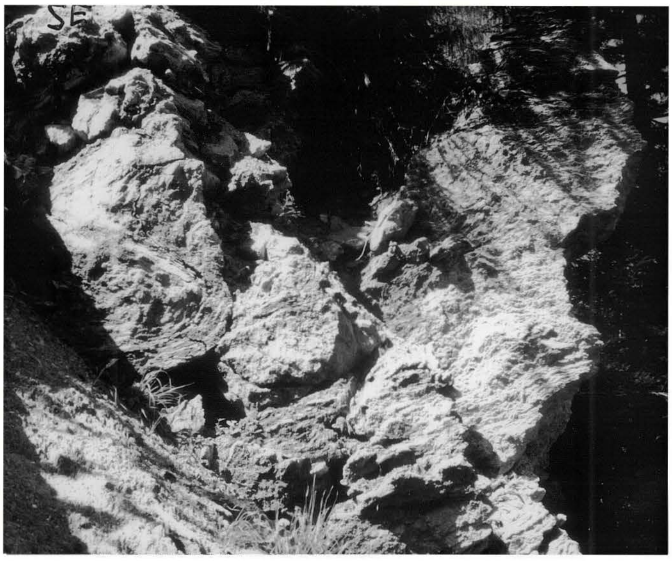
site derived from Raibl beds was brought to the surface by south-vergent thrusting (Figs 11, 12). This thrust must have cut the Hauskogel nappe as well (Fig. 12B). Hence, subsequent normal faulting is needed to bring the Hauskogel slice in contact with the basement of the Hohenegg slice (Fig. 12C). The contact between "Alpiner Buntsandstein" and Raibl ultracataclasites implies intense thinning before thrusting similar to the Hauskogel slice and rapid wedging out of the Hohenegg slice towards the northwest.

The geometry of faults around the Tondlkopf is not completely understood at the time being. The westward continuation of the Wetterstein Dolomite south of the Hohenegg slice is an effect of dextral strike slip faulting, indicated by brittle fault planes and foliation at the contact between Hohenegg and Hauskogel slice north of the Tondlkopf. However, there seems to be no continuation of this fault zone to the east, across the fault parallel to the Maukenbach.

A local study of coalification in the Brixlegg area demonstrated, that there is a smooth decrease in coal rank from bottom to top and from south to north (Rantitsch, G. and Russegger, B., pers. comm.). The stacking of slices must have taken place before or during metamorphism, offset of all other movements younger than metamorphism were not sufficient to cause detectable jumps in coal rank.

Schwaz area

In the Schwaz area only the Hohenegg slice exists. The youngest rocks preserved are siltstones of the Raibl For-



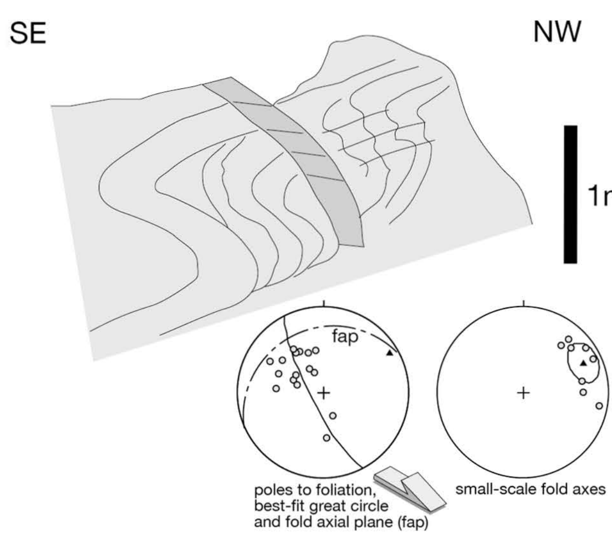


Fig. 9 - Small-scale folds in the ultracataclasite east of the Maukenbach. The folds indicate a top SSE movement of the hanging wall.

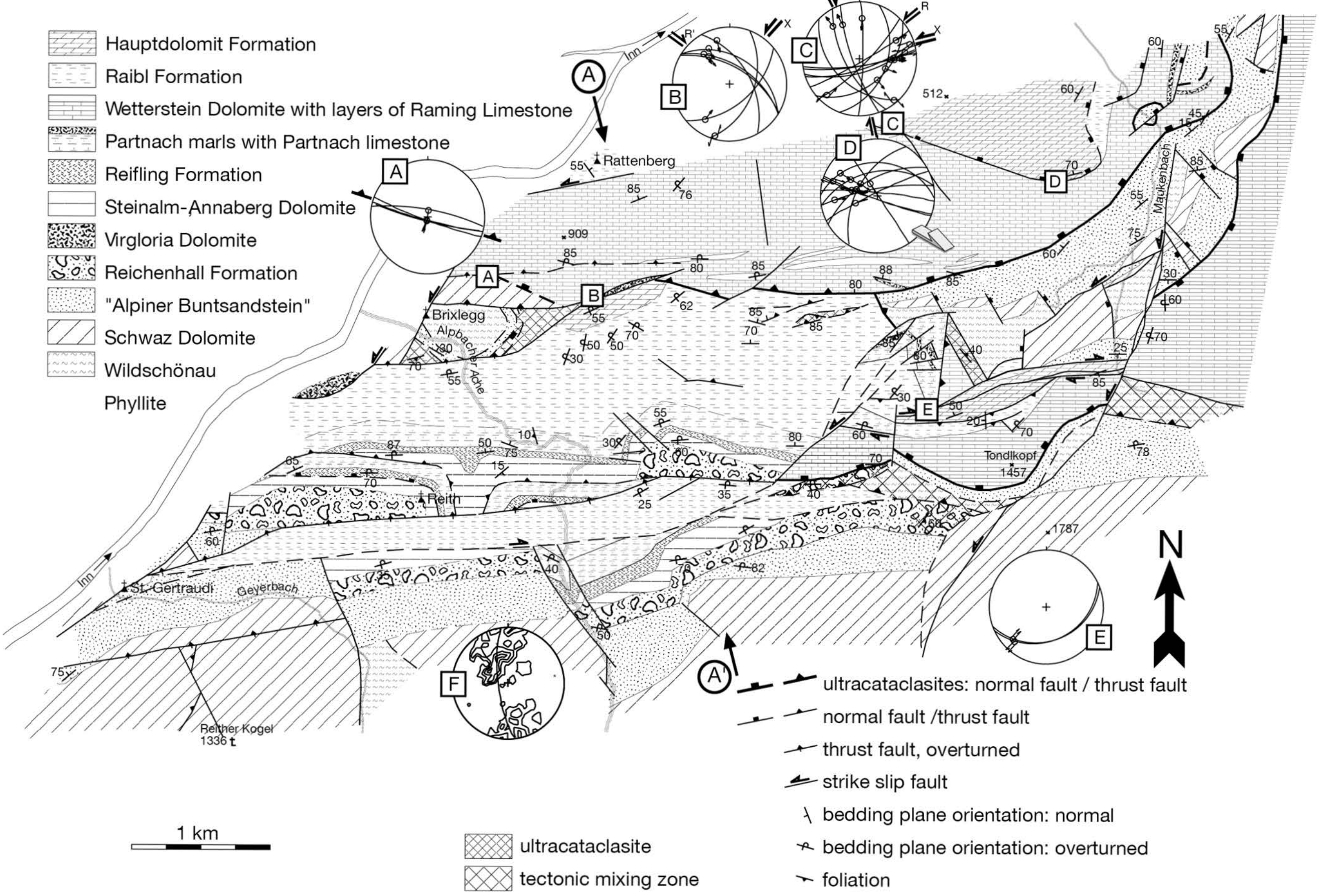


Fig. 10 - Geological sketch of the Brixlegg area. Quaternary sediments not shown for clarity. The Wetterstein and Hauptdolomite successions south of Rattenberg and around the Tondlkopf and the basement and "Alpiner Buntsandstein" units around the Maukenbach are part of the Hauskogel slice. Diagrams: (A) example for south-directed overturned thrusts; (B), (C) examples for sinistral shearing; (D) tilted fault planes belonging to the top SE extension; (E) dextral shearing; (F) contoured poles to bedding planes from the Hohenegg slice indicating N-S compression. Lower hemisphere plots: R, R' ... synthetic and antithetic Riedel planes, X ... master fault.

mation. Gypsum horizons are not known, neither in the Reichenhall nor in the Raibl Formations.

The contact between the Greywacke Zone and the Northern Calcareous Alps is mostly in a vertical to overturned position and runs more or less parallel to the Inn Valley. A steep basement/cover contact in the Schwaz area, extending downward some 100 m is known from deep (abandoned) mining galleries which are located below today's valley floor. The geological map can therefore - in great parts - be considered as a cross section (Figs 13, 14).

In terms of deformation style two distinctive "stockwerke" can be distinguished: "Alpiner Buntsandstein" and Schwaz Dolomite react as 100 m to km size fault blocks with minor (alpidic) internal deformation, mainly m to 10 m -scale folding. In contrast the mixed carbonatic / shaly triassic part of the succession exhibits intensive folding in 10 m to 100 m scale. In between the evaporitic Reichenhall beds act as decoupling horizon. This mobile zone contains fault blocks consisting of Schwaz Dolomite as well as blocks of Partnach Formation. (Fig.13, details 3a

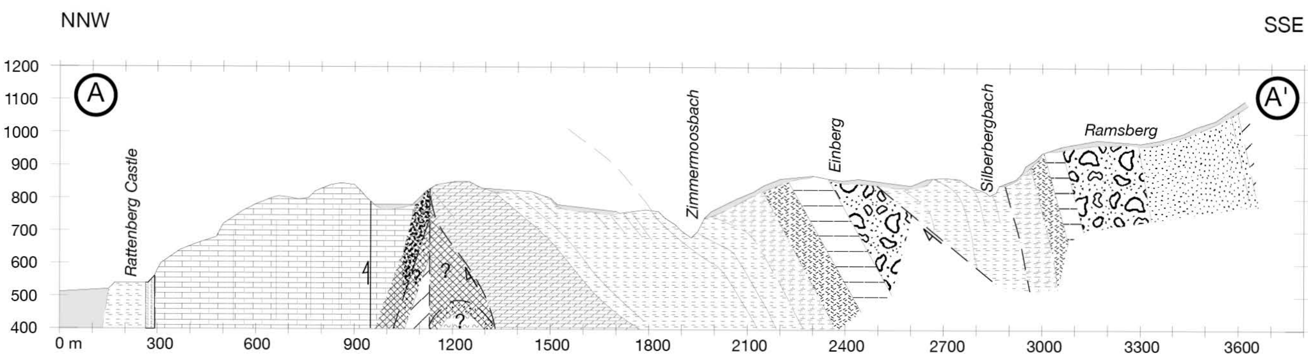


Fig. 11 - Cross section from the Brixlegg area. Stratigraphy of the Hohenegg slice is doubled by an overturned reverse fault south of Einberg. Near 1200 m basement of the Hohenegg slice is thrust by a similar fault onto the Hauptdolomite Formation of the same slice.

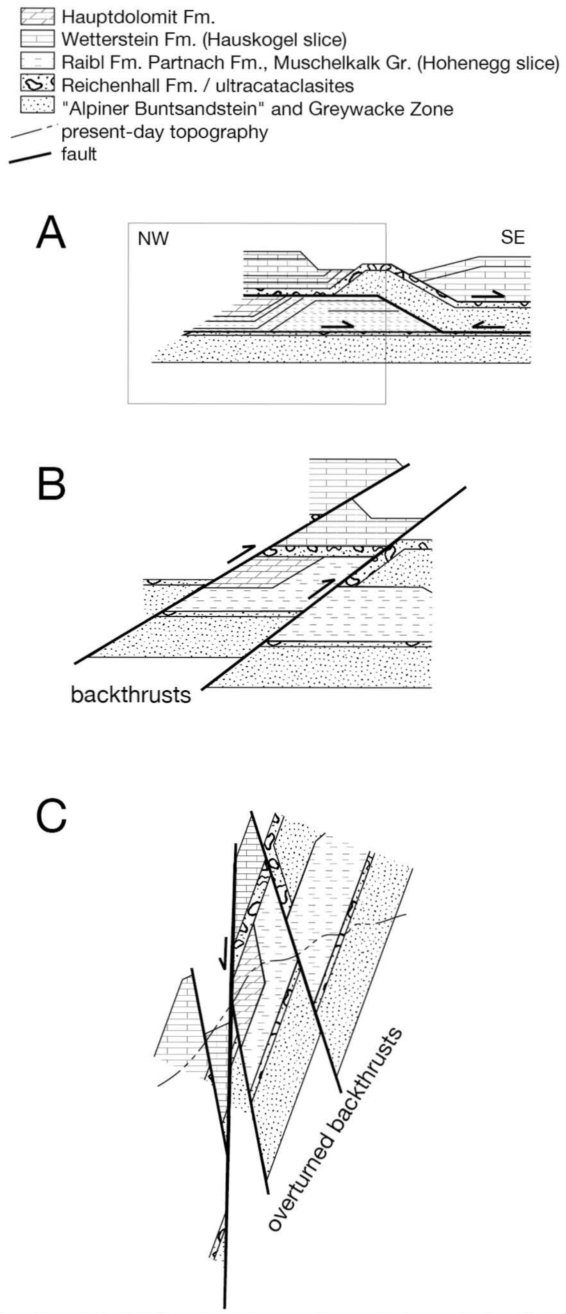


Fig. 12 - Model for the kinematic evolution of the Brixlegg-Wörgl area. (A) Stacking of thinned slices. A roll-over anticline in the lower Hohenegg slice is cut by out of sequence thrusting of the Hauskogel slice. The units in the square are tilted to the north later. (B) South-vergent thrusting in the deformed nappe stack causes doubling of the stratigraphy in the present-day outcrops. (C) Young normal faulting brings the "Alpiner Buntsandstein" and basement slice on the left into contact with Wetterstein Dolomite of the Hauskogel slice.

and b). The latter is also a common constituent of evaporitic-tectonic breccias which also contain sliced Reichenhall Dolomites.

We explain this arrangement as the result of polyphase movement of a ramp-flat systems fault that climb from the basement up to the Raibl Formation. On top of the "Alpiner Buntsandstein" the Reichenhall Formation forms a flat. An apparent" normal" stratigraphic succession with exotic fault blocks in between can be produced when extensional movements are compensated by compressional movements or vice versa: horses of basement or of higher stratigraphic units get trapped in a large-scale shear zone. Shear sense criteria from fault zone rocks give both top E and top NW movements (Fig. 15), supporting a contrary movement history.

On the map, a two-phase fold interference pattern can be recognized. 100 m scale folds correlate with top NW thrusting direction. These folds are overprinted by WNW-ESE trending folds producing strong undulations of first generation fold axes. This N(NE)-S(SW) compression might also be responsible of the overall steepening and overturning of the successions (including the basement, *cf.* Fig. 14).

Brittle ENE-trending sinistral faults parallel to the Inn Valley (newly-formed) overprint this pattern in some parts. Most of these planes are in subvertical position today, only some sinistral rotation occurred in the NW part of the study area. Therefore we infer an onset of sinistral faulting in a late stage of N(NE)-S(SW) shortening.

Relationship between heating and deformation:

Top E normal faulting and top NW thrusting both took place during low to very low grade metamorphism. While limestones reacted ductilely in some parts, ramps in quartz-sandstones also proof top NW thrusting, but in a brittle environment. Therefore temperature/fluid conditions in this stage must have been in favour of ductile behaviour of calcite and brittle behaviour of quartz/dolomite.

A local study of conodont alteration indices (CAI, after Epstein *et al.*, 1977) within the Reifling and Partnach horizons reveals a rather constant heating pattern of CAI 3-4 (corresponding approximately to 250° C) and plots in the same temperature range as the contrasting deformation styles of limestones and dolomites/quartz-sandstones suggest. Some high-temperature spots (around CAI 5) can be correlated with faults and local occurrence of saddle dolomites.

METAMORPHIC EVENTS DEDUCED FROM GEOCHRONOLOGY

A sample from marly Reifling limestones near Schwaz yielded a K-Ar isochrone model age of 122 - 117 Ma from white mica fine fractions (Krumm, 1984). To the east of the Gaisberg Triassic, several K-Ar ages between 95 and 140 Ma were reported (Kralik *et al.*, 1987). These ages were interpreted as mixing ages between an Early Cretaceous and a Tertiary metamorphic event (Kralik *et al.*, 1987). Modelling of the temperature history of the Lechtal nappe/Upper Bajuvaric unit in the Arlberg region, 120 km to the west of the investigated area by Ferreiro-Mählmann and Petschik (1996) suggests a temperature peak at 140 Ma, and a second, slighty weaker metamorphic event at 60 Ma. The 140 Ma temperature event was found also by Spötl *et al.* (1996), who could date the growth of diagenetic albite in the Tirolic unit to that time in the area of Salzburg 80 km to the east of the investigated area. The second metamorphic event is recorded by apatite fission track ages from the southern margin of the Northern Calcareous Alps (Tirolic unit) south of Salzburg by Heijl and Grundmann (1989) and Stauffenberg (1987) around 60 Ma. However, from Salzburg to the west, apatite fission track ages by Grundmann and Morteani (1985) become progressively younger. In the Greywacke Zone near the Gaisberg Triassic, an age of 42 Ma is reported, southeast of Kundl 23 Ma and near Schwaz ages between 9 and 17 Ma. This may reflect the

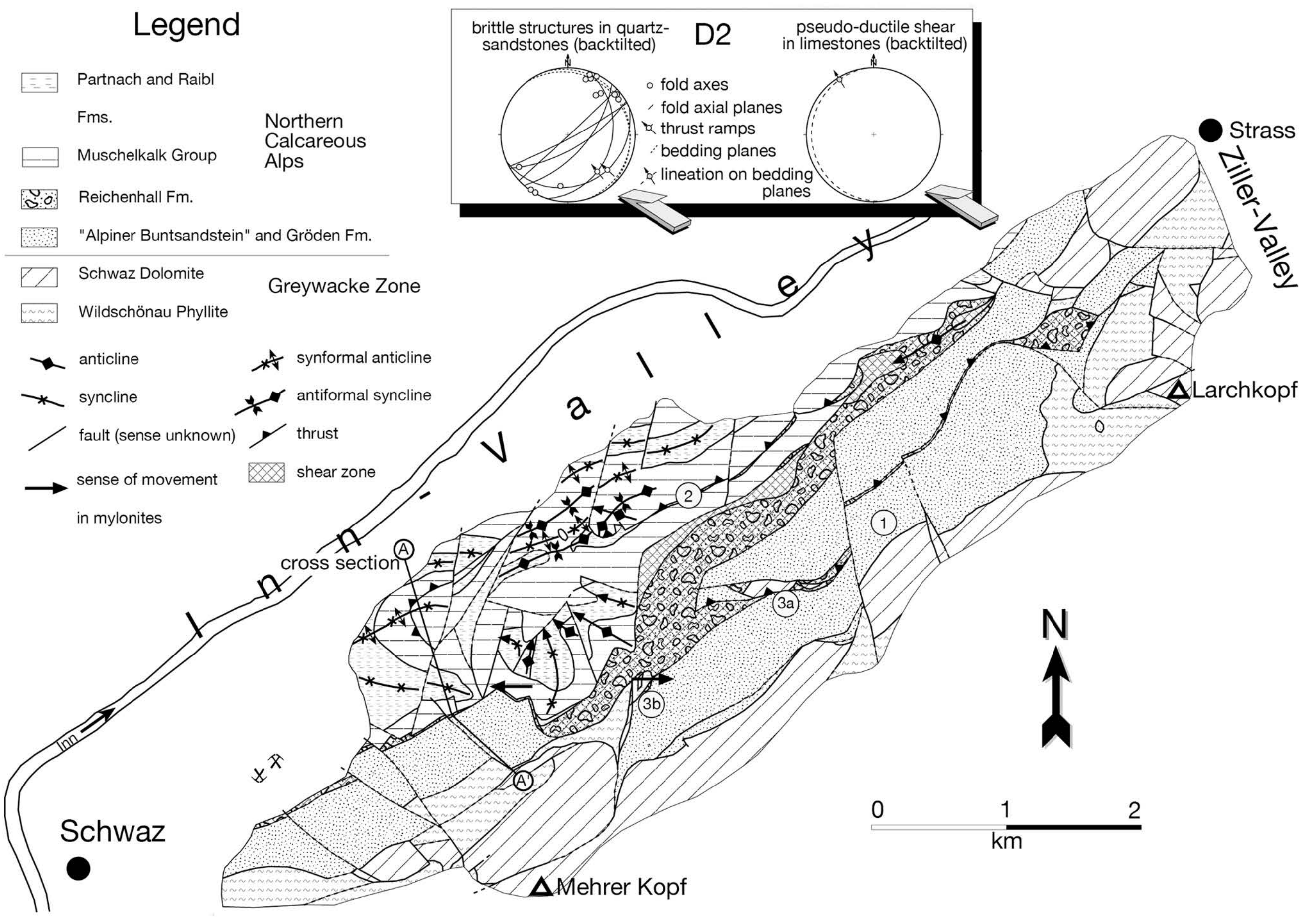


Fig. 13 - Tectonic sketch map of the Schwaz area. Permoscythian clastics in parautochthonous contact with the basement act as rather brittle fault blocks. Stratigraphically higher cover rocks are intensely folded and sliced. The succession is repeated on top of the "Alpiner Buntsandstein" (1) and Muschelkalk (2). (3a) and (3b) denote fault blocks of Schwaz Dolomite and Partnach limestone, respectively. For details see text. A-A' denotes the cross section in Fig. 14.

thermal overprint by Oligocene-Miocene metamorphism during formation of the Tauern Window core complex (Fig. 1; Selverstone, 1988). Zircons from the Lower Austroalpine unit southwest of the investigated area yield fission track ages around 60 Ma (Fügenschuh, 1995), similar to the Northern Calcareous Alps east of the investigated area corresponding to the Tertiary metamorphic event.

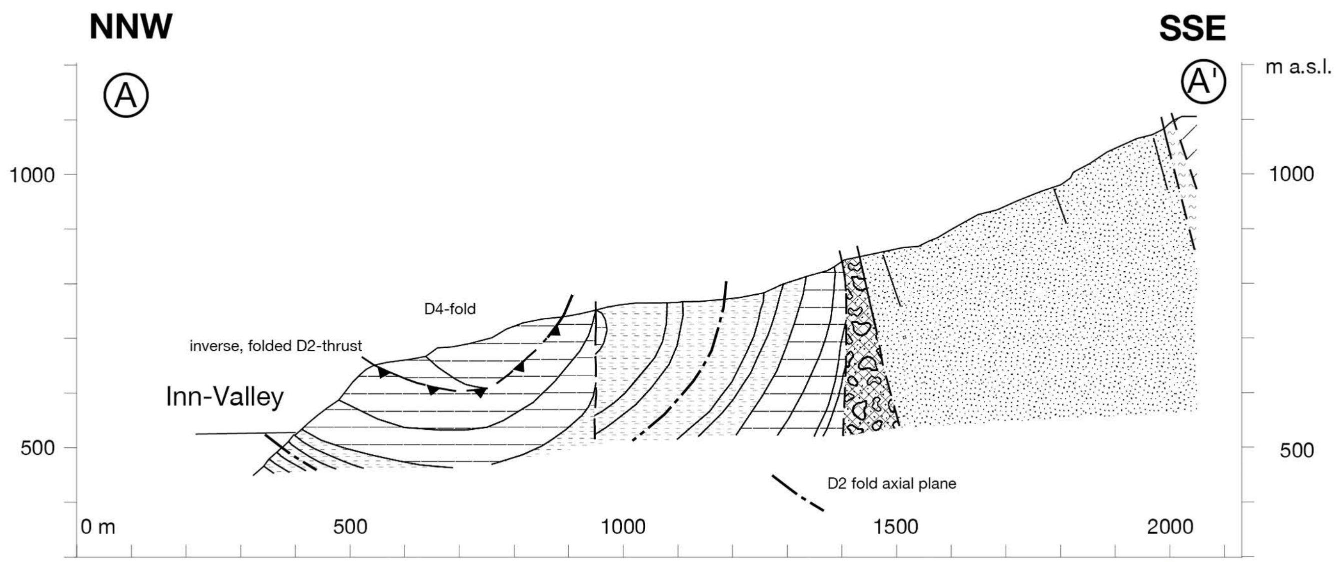


Fig. 14 - NW-SE cross section at the western end of the Schwaz area. A tight to isoclinal syncline in 100 m scale with Partnach shales in the core and a minor thrust within the Muschelkalk-niveau (today overturned) are refolded. The basement/cover contact (here not primary) and the top of the Permoscythian clastic succession are in steep to overturned position.

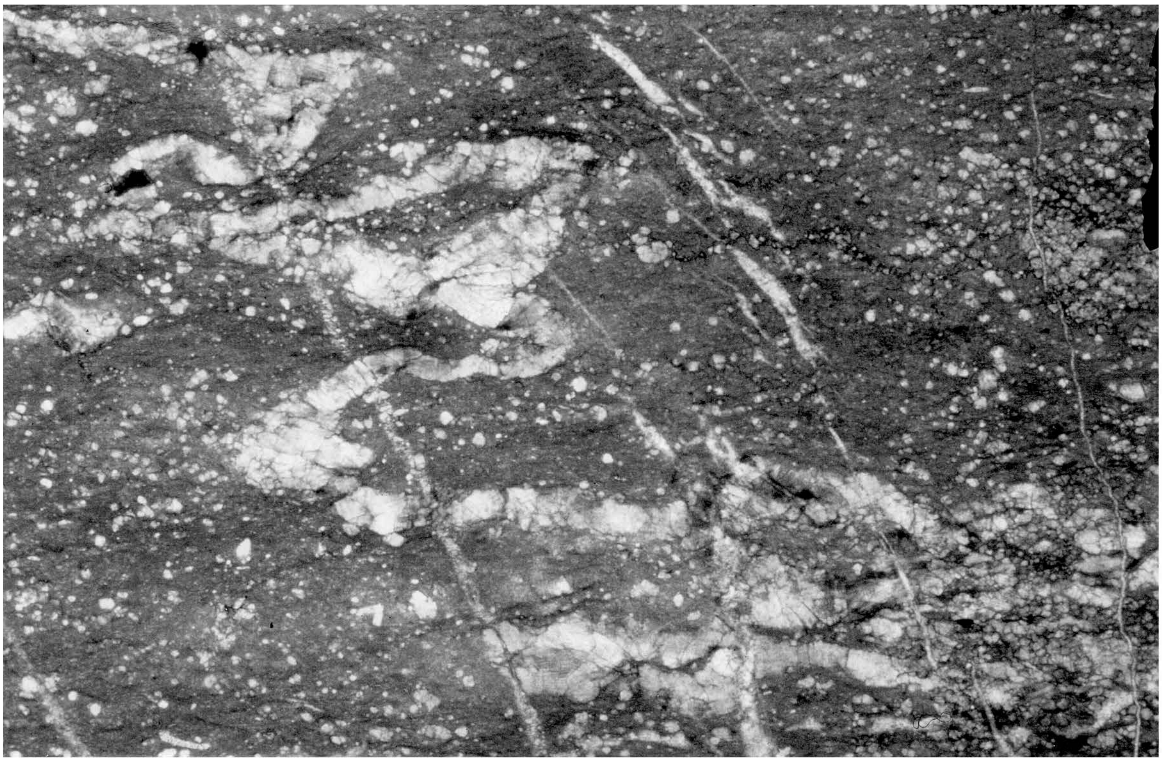


Fig. 15 - Thin section of a partially dolomitized limestone with mylonitic fabric. A dolomite vein was ptygmatically folded during later shearing of the rock. Shear sense is top the left (west).

DISCUSSION

Still there are some contradictions persisting over the general scheme of deformational and metamorphic history comparing the subareas: normal faulting in the Gaisberg area displaces metamorphic isogrades and therefore should be younger than metamorphism and ductile deformation of "Alpiner Buntsandstein" breccias before 60 Ma (apatite fission track ages; Stauffenberg, 1987; Hejl and Grundmann, 1989; see above). In contrast, normal faulting in the Schwaz-Wörgl area does not displace isogrades. The normal faults in the Schwaz-Wörgl area are reactivated by ductile top NW compression. If it is assumed, that ductile deformation occured contemporaneously in the entire investigated area, two top SE extensional events have to be assumed, one before and one after ductile compression.

Ductile compression in the Gaisberg area (top N) is oriented in a different direction compared to areas further to the west (top NW). A possible explanation could be a differential rotation of single blocks of the Austroalpine nappe pile postdating the ductile deformation. Analogous rotations were observed in parts of the Northern Calcareous Alps as well: Late Cretaceous sediments seal folds in the Eiberg Gosau basin trend NE-SW (Gruber, 1997), while folds sealed by the Glasenbach Gosau near Salzburg trend NW-SE (Schweigl and Neubauer, 1997).

The latest phase of metamorphism acts contemporaneously with the sedimentation of synorogenic clastics (Gosau sediments) on top of the Upper Austroalpine nappe pile (structural difference 1-2 km). However, the primary distance between the sedimentation area and the Greywacke Zone basement was modified during later shortening and the thermal history of the area is not well constrained. It is not clear, whether there was continuous slow cooling from the thermal peak around 140 Ma until around 60 Ma (apatite closure), or if the area cooled until the onset of Gosau sedimentation and was reheated by a second, weaker metamorphic event.

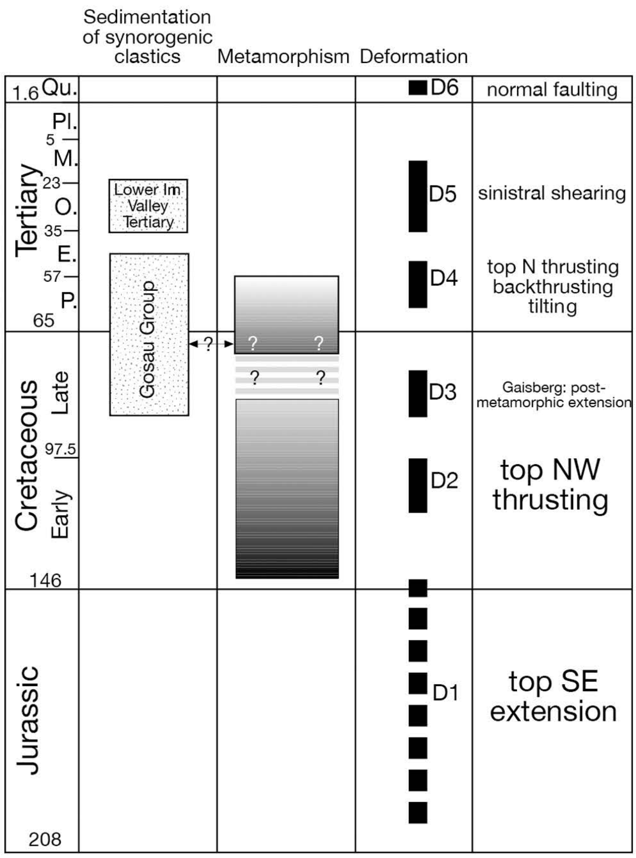


Fig. 16 - History of synorogenic sedimentation, deformation and metamorphism at the southern margin of the Tirolic unit. Abbreviations: P...Paleocene, E...Eocene, O...Oligocene, M...Miocene, Pl...Pliocene. Q...Quaternary. Ages after Harland *et al.* (1990).

CONCLUSIONS

The history of deformation of the Triassic south of the Inn Valley is summarized as follows (Fig. 16):

D1: Thinning by top SE extension. The extensional movements produced ultracataclasites along the decollements. In the area between Brixlegg and Wörgl (Hauskogel slice), the Muschelkalk Group is removed by normal faulting. The minimum estimate for the horizontal offset is 6 km. Except for some older faults in the "Alpiner Buntsandstein", this is the oldest Alpine deformational event and might be associated with the Jurassic continental breakup.

D2: The D1 detachment is refolded into NE-trending folds generated by top W or NW compression associated with dextral NW-trending strike slip faults. In the Inntal Nappe, folds with NE-trending axes are sealed by Late Cretaceous sediments. D2 is contemporaneous with peak meatmorphic temperatures and the stacking of slices in the area. We assign D2 to eoalpine deformation and metamorphism, which represents nappe stacking in the foreland of the closure of the Meliata ocean (*e.g.* Neubauer, 1994; Froitzheim *et al.,* 1996).

D3: Post- or late-metamorphic top ESE low-angle normal faulting offsets illite crystallinity isogrades in the Gaisberg area. This deformation is roughly contemporaneous with Gosau sedimentation in the same tectonic unit further north (Gosau SW of Kufstein; Fig. 1; Gruber, 1997) and top SE normal faulting in the Middle Austroalpine units (Fügenschuh, 1996).

D4: A second compression produced northvergent fault propagation folds with an axial plane cleavage in the shaly units of the investigated region. The units west of Kundl were stacked by backthrusting and overturned (Fig. 12). Illite-crystallinity data, CAI-values and vitrinite reflectance data from the vicinity of Brixlegg do not display jumps across the decollement levels, but a gradual decrease in metamorphism from south to north. Offset across D4 thrust faults was not sufficient to produce significant jumps in the coalification pattern. D4 is interpreted to be related to the closure of the Penninic realm in the Eastern Alps and emplacement of the Austroalpine nappe stack onto the European margin (*e.g.* Frisch, 1979; Froitzheim *et al.,* 1996).

D5: A period of sinistral shearing along ENE-trending faults (Inn Valley shear zone) is kinematically connected to minor backthrusting in the Brixlegg area. Northeast of the investigated area, Oligocene sediments were deposited in a pull-apart basin during D5 (Fig. 1). The basin fill was subsequently deformed by renewed activity of the sinistral faults during the Miocene (Ortner and Sachsenhofer, 1996).

D6: Young E-W-trending normal faults cut the sediment stack.

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